

KINEMATIC AND KINETIC ANALYSIS OF SQUAT JUMP AND COUNTER-MOVEMENT JUMP

A Thesis Submitted in Partial Fulfillment
of the Requirement for the Degree of

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CERTIFICATE

This is to certify that the report entitled “**KINEMATIC AND KINETIC ANALYSIS OF SQUAT JUMP AND COUNTER-MOVEMENT JUMP**” submitted by **Subhashish Kumar Satpathy (111BM0546)** towards the partial fulfillment of the requirement for the degree of Bachelors of Technology in Biomedical Engineering at Department of Biotechnology & Medical Engineering, NIT Rourkela is a record of bonafide work carried out by him under my guidance and supervision.

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ABBREVIATIONS

| | |
|--------------|--------------------------------------|
| ADC | = Analog to digital converter |
| CM | = Counter-movement |
| COM | = Center of mass |
| DAQ | = Data acquisition system |
| EMG | = Electromyography |
| FM1 | = Head of first metatarsus |
| FM5 | = Head of fifth metatarsus |
| GRF | = Ground reaction force |
| QTM | = Qualisys track manager |
| R_FAL, L_FAL | = Fibula apex of lateral malleolus |
| R_FLE, L_FLE | = Femur lateral epicondyle |
| R_FME, L_FME | = Femur medial epicondyle |
| R_FTC, L_FTC | = Femur greater trochanter. |
| R_ICT, L_ICT | = Ilium crest tubercle (Iliac Crest) |
| R_TAM, L_TAM | = Tibia apex of medial malleolus |

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ABSTRACT

This study presents the investigation of maximum height of jump for volunteers executing a squat jump and counter-movement (CM) jump. This analysis was carried out with the help of a 3D motion capture system. The study was aimed at finding out the difference in jumping patterns and jump height for specific groups of participants comprising individuals regularly involved in sports activities and others who rarely take part in a specific sports activity. The ground reaction force (GRF) patterns are utilized in order to analyze both types of jumps. Variation of the maximum jump height in contrast to the knee angle, hip angle and ankle angle was studied. The gait cycle of the jump has essentially four parts: crouch phase, push-off phase, flight phase and landing phase. The change in GRF serves as an indicator for the momentum change of the center of mass. The GRF value decreases at the time of crouch phase and again increases with change in acceleration for counter-movement jump. The decrease in GRF value produces a negative impulse and accordingly negative kinetic energy. In push-off phase a positive kinetic energy is developed which should be more than the kinetic energy developed in crouch phase to attain maximum height of jump. To achieve maximum height of jump the knee angle before take-off varies from 80° to 100° and the hip angle varies from 70° to 90° . Hence at a hip angle of 90° the maximum jump height is achieved according the experimental data. It is observed that moment at the knee angle and hip angle will be maximum for 90° joint angle. Due to maximum moment about the knee and hip joint, jump height attained will be maximum.

Keywords: jump, counter-movement, motion capture, ground reaction force, knee angle

Chapter 1

Introduction

1.1 Overview

Most of the sports like basketball, volleyball, football, etc. involves lots of lower body movement. To achieve a maximum jump height while playing real life sport, the sportsperson has to train their body accordingly. The participant applies a force against a substrate, which generates a reactive force that propels the participant away from the surface. Any solid or liquid capable of producing an opposing force can serve as a substrate, including ground or water. This study is based on the jumping activity of two different types of standing jumps i.e. squat jump and counter-movement jump. In squat jump the moment generated from the upper body is restricted by crossing the arms. The participant starts from an upright standing position, makes a preparatory descending motion by flexing the knees and hips so that the thigh is parallel to the ground, then extends the knees and hips again to hop vertically up off the ground. In counter-movement jump the participant uses the moment and muscle action from upper body also to achieve a maximum height. Squat jumping is a basic exercise in sports training to strengthen the muscles of the lower body. A jumping pattern can be essentially divided into four phases: crouch phase, push-off phase, flight phase and landing phase [1]. Crouch phase represents the transition from standing posture to the maximum flexion of knee and hip joints. Push-off phase represents the extension of knee and hip until the take-off of the body. Flight phase represents the interval between take-off and landing when the body is in air. The landing phase represents the part when the foot comes into contact with the ground surface. From a review of data presented by researchers it is known that the jump height of counter-movement jump is more than that of a squat jump [2]. This can be attributed to the additional moment and muscular energy input from the action of upper body segments. To study the parameters one first needs to understand the functioning of biomechanical instruments and learn about human gait analysis.

1.2 Sports biomechanics analysis

The sports biomechanics analysis are carried out by qualitative and quantitative methods. The qualitative analysis is descriptive in nature and performed in four steps[3]. The method presented here includes procedures common to existing methods and provides a systematic way of biomechanically analyzing human movements.

A qualitative biomechanical analysis to improve technique involves four steps i.e. description, observation, evaluation, and instruction. Description is the process of developing a theoretical model of the most effective technique and describing what it would look like. This is to observe the performance of the participant to determine what the technique actually looks like. Evaluation involves the comparison of the observed performance to the ideal technique and to identify and evaluate the errors. The performers are needed to be acknowledged about the feedbacks and the instruction necessary to correct those errors. The analysis has to be repeated again to minimize the error.

A quantitative analysis involves measurement of the parameters of performance. The resulting analysis based on these measurements is a quantitative biomechanical analysis. As the level of performance increases, the magnitude of the errors in performance decreases. Errors made by novices are large and easy to detect visually using qualitative biomechanical analysis techniques. With improved performance, the errors decrease in size and become more difficult to detect; and at the elite level, a comprehensive quantitative biomechanical analysis may be necessary to detect them.

1.3 Gait analysis

Gait analysis is the systematic study of animal locomotion, more specifically the study of human motion, using the eye and the brain of observers, augmented by instrumentation for measuring body movements, body mechanics, and the activity of the muscles [4]. It has a wide area of application in sports biomechanics. The measurement of the

variables of the gait is mostly done by the use of a force platform and 3D motion capture system. Other instruments like force transducers (strain gauge), pressure sensors, EMG (electromyography), velocity meters etc. can be used for specific quantity measurement. Gait analysis is generally carried out by the measurement of ground reaction force (GRF) patterns in order to identify the phases involved in the type of motion under study.

1.4 3D motion capture system

3D motion capture is a process of capturing real-time trajectories of various segments of the human body with the use of high-speed cameras. This process involves the attachment of passive markers at specific anatomical locations of a subject's body. For a biomechanics study the motion capture system is capable of capturing joint and segmental motion of the body parts such as head, upper body and lower body. Even small scale body movement such as facial expression can be captured with this system, although it requires the use of other professional software for post-processing. The motion capture system consists of a set high speed infra-red cameras integrated with the computer and an interfacing software to process and display the captured data by means of marker trajectories. Two types of motion capture systems are available, one being marker-less motion capture system and the other being the motion capture system which makes use of either active or passive markers for recording data. The system used in this study is of the latter kind, making use of passive retro-reflective markers. The system allows to capture 2-dimesional, 3-dimensional, and 6-degree of freedom data in real-time with minimal latency. The markers are used to define the spatial locations of various anatomical segments of the human body by attaching them on the medial and lateral orientations of appropriate joints. The retro-reflective markers act as an enhanced reflecting medium which reflects the infra-red light emitted by the diodes surrounding the aperture of the cameras. The retro-reflective markers are of special construction in that not only do they

reflect a particular wavelength of light properly, but they also provide a large angle of reflection, which is essential in order for multiple cameras to capture the reflected light.

The process of motion capture involves the steps of initialization or calibration, tracking, pose estimation, and recognition. Initialization of the system is carried out by proper placement of the cameras followed by synchronization with the system. Before conducting trials calibration of the lab volume is done with the help of a standardized calibration kit. After initialization the system has to capture the motion executed by the body. In the tracking process the trajectories of individual markers are obtained through an interfacing software. Pose estimation is the process where with the individual markers are visually recognized by the user and the corresponding anatomical notations are assigned. Recognition is the process where the user identified markers are used to define and generate the body segments in a representative static model. This process is usually carried out with the help of a post-processing software. Some such post-processing software contain predefined musculoskeletal models of the human body and only require the user input to organize the segmental parts in tandem with the dynamic location of identified markers.

With the help of the 3D motion capture system one can analyze the kinematics of the human body. From the motion capture system the linked based parameters such as distance, velocity, acceleration, the angle between two segments (joint angle), joint moment, energy of the segments etc. can be obtained. For kinetic analysis a multi-axial force platform is integrated to the system so all the biomechanics parameters which are needed for the analysis can be obtained.

1.5 Multi-axial force platform

Force platforms are used in clinical gait laboratories to assess the effectiveness of treatments of patients having neuromuscular diseases or to assess the progress of

rehabilitation from musculoskeletal injuries. The patterns revealed in the force– time plots give coaches and scientists information about differences in technique that may affect performance.

The force platform has a very simple construction. The load on the force platform is shared by four piezo-electric transducers positioned at the four corners. The voltage output from the transducers is directly proportional to the load applied on the platform and subsequently to the GRF offered by the ground. Each piezo-electric transducer will generate a charge proportional to the load shared[5]. The output is then converted to voltage using the equation

$$V = \frac{Q}{C} \quad - (1)$$

Where, V = voltage, Q = charge generated when the force is applied and C = capacitance.

Chapter 2

Literature

Review

While performing a squat jump, the lower limbs produce mechanical work to elevate the center of mass from its initial vertical position to that of maximal height. At the initial position the vertical velocity (and hence kinetic energy) being zero, the total work done can be calculated as the change in potential-energy from the initial vertical position and maximum height position [6].

Furthermore, the mean power (P) development of the lower limb is [6]:

$$P = mg \left(\frac{H}{H_{po}} + 1 \right) \sqrt{\frac{gH}{2}} \quad - \text{eq (2)}$$

Where m = the body mass, g = the gravitational acceleration, H_{po} = the vertical push-off distance and H = the jump height.

The ability to quickly accelerate the body from a resting position is considered to be particularly important for successful performance in many sport activities. Based on Hill's muscle mechanical model, this “explosive” ability is directly related to the mechanical characteristics of the muscle contractile component, and maximal power output [6]. Further, testing the maximal power output of lower limbs extensor muscles is a common practice in the assessment of human exercise performance [7].

Different formulae have been proposed to estimate power output from vertical jump height and body mass. Some of them are derived from fundamental laws of mechanics but challenged due to the biomechanics model. Indeed, it has been argued that Lewis's formula divides the change in potential energy by the aerial ascending phase duration instead of that of the push-off, and does not take into account the change in potential energy during push-off. Gray's formula assumes that the vertical acceleration of the center of mass (COM) is constant during push-off, which is in contradiction to some experimental results frequently presented in the literature[8].

The maximum height of jump is greater in case of CM jump in comparison to that of a squat jump. Various researchers have speculated musculoskeletal action as the reason behind this phenomena. Pre-stretching allows the muscles to develop a high level of active state and generate a larger force before starting to shorten[9]. Other researchers attribute the sudden release of elastic energy stored in the muscles and tendons to the extra work required to attain a greater jump height [10]. Another study on the proteins of muscles explains the enhancement through the ‘potentiation’ of the contractile proteins of the muscle or because of the spinal reflexes [11].

The use of arm moment in counter-movement jump increases the jump height by increasing vertical take-off velocity. The work done at hip joint is increased by the movement of arms but the effect on knee and ankle joint is negligible[12]. With a shorter push-off duration and small movement, the moments and mean power output at the knee and ankle were found to be larger in drop jump than in counter-movement jump [13]. Athletic individuals exhibited a larger magnitude of joint moment, power and work at the ankle, knee and hip joints and therefore attained greater jump height. This shows that a higher jump height for athletes is influenced to a high degree by the large amounts of energy generated at the driving joints rather than the techniques adopted for execution[14].

Objectives

The main objectives of this current study are:

1. To study the pattern of forces for a squat and counter-movement jump performed by a group of athletic and non-athletic individuals.
2. To compare and study the maximum jump height for athletes and non-athletes in case of squat and counter-movement jumps.
3. To analyze the jump height with respect to the different parameters such as knee angle, ankle angle and hip angle.

Chapter 3

Methodology

3.1 Equipment and software

3.1.1 3D motion capture system

The 3D motion capture system consists of four infra-red Oqus cameras, an integrated multi-axial force platform and Qualisys proprietary tracking software (QTM, Qualisys track manager). Qualisys' proprietary tracking software allows users to capture 2-dimensional, 3-dimensional and 6-degree of freedom data in real-time, with minimal latency.

3.1.2 Multi-axial force plate

The force platform used in this study was Kistler's multiaxial force platform (model AA9260) shown in **Figure 1**. The dimensions of the plate are 500×590× 50 mm. This force platform can measure ground reaction forces (GRF), moments, torque, center of pressure, coefficient of friction, velocity, acceleration, work done, impulse and displacement of the center of mass of the body.



Figure 1: Force plate used in this study

3.1.3 Data Acquisition System (DAQ)

The integration of force platform with the 3D motion capture system is achieved with the help of Kistler's data acquisition system (DAQ) (type 5691A1). The analog output from

the force platform passes through an internal amplifier and reaches the DAQ where data sampling is done to generate a digital signal. Simultaneously the marker position data is acquired from Oqus high-speed cameras is synchronized with the digital output of the force platform data. This synchronized data is reflected in Qualisys track manager software.

3.1.4 Qualisys Track Manager software

Qualisys Track Manager is a Windows based data interfacing software with an interface that allows the user to perform 2D and 3D motion capture. QTM is designed to provide both advanced features required by technically advanced users and a simple method of application for the inexperienced user. Together with the Qualisys line of optical measurement hardware, QTM will streamline the coordination of all features in a sophisticated motion capture system and provide the possibility of rapid production of distinct and accurate 3D, 2D and 6DOF data. During the capture, real time 3D, 2D and 6DOF information is displayed allowing instant confirmation of accurate data acquisition. The individual 2D camera data is quickly processed and converted into 3D data by advanced algorithms, which are adaptable to different movement characteristics. The data can then be exported to analysis software via several external formats.

3.1.5 Visual3D V5 professional software

Visual3D is a proprietary general purpose bio-motion modeling and analysis software package developed and published by C-Motion, Inc. The software makes use of the .c3d file format for input data as well as real-time motion data streamed by several hardware manufacturers. The program is not restricted in terms of marker sets and provides a historical audit trail of data changes. Modeling features include kinematics, inverse dynamics (kinetics) and inverse kinematics.

3.1.6 Retro-reflective markers

The retro-reflective markers are made of polystyrene hemispheres covered in special retro-reflective tape [15]. The markers used are 11.9 mm in diameter. Eighteen markers and eight tracking markers are used in the course of the study (**Figure 2**).



Figure 2: Retro-reflective marker used in motion capture analysis

3.2 Methods

3.2.1 Setup of the system and volunteers

The system consists of four infra-red cameras and a force plate (**Figure3**). QTM serves as an analytical tool for the system. The digital output of the system acts as input for the software. The laboratory volume is calibrated (using a standardized calibration kit) before recording the trials. Any residual errors in the calibration must be less than 0.1mm. If larger errors are obtained, then recalibration of the system must be performed. To obtain accurate position of markers, recalibration of the system was performed after every 24 hours, as suggested in the standards.



Figure 3: Laboratory set-up of the motion capture system at NIT Rourkela

Volunteers

For this study twenty volunteers were selected from within the institute. The volunteers were characterized into two groups, namely athletic and non-athletic participants. The athletic volunteers are belonged to different sports background such as basketball, volleyball and football whereas the non-athletic participants were not involved in any regular sports activity. All the volunteers for this study were aged between 19 and 24 years. Informed consent was obtained from each participant before conducting the trial.

The retro-reflective markers were attached to distinct anatomical points on the lower body. Eighteen markers and eight tracking markers were used in each case to represent the lower body (**Figure 4**). In the course of this study each volunteer was made to jump on the force plate. The markers were named according to the anatomical position of the body. For lower body the markers used were named as R_ICT, L_ICT, R_IAS, L_IAS, R_FTC, L_FTC, R_FLE, R_FME, L_FLE, L_FME, R_FAL, R_TAM, L_FAL, L_TAM, R_FM5,

R_FM1, L_FM5, L_FM1 and tracking markers can be named according to choice. The positions are specified in (Figure 5) shown below.

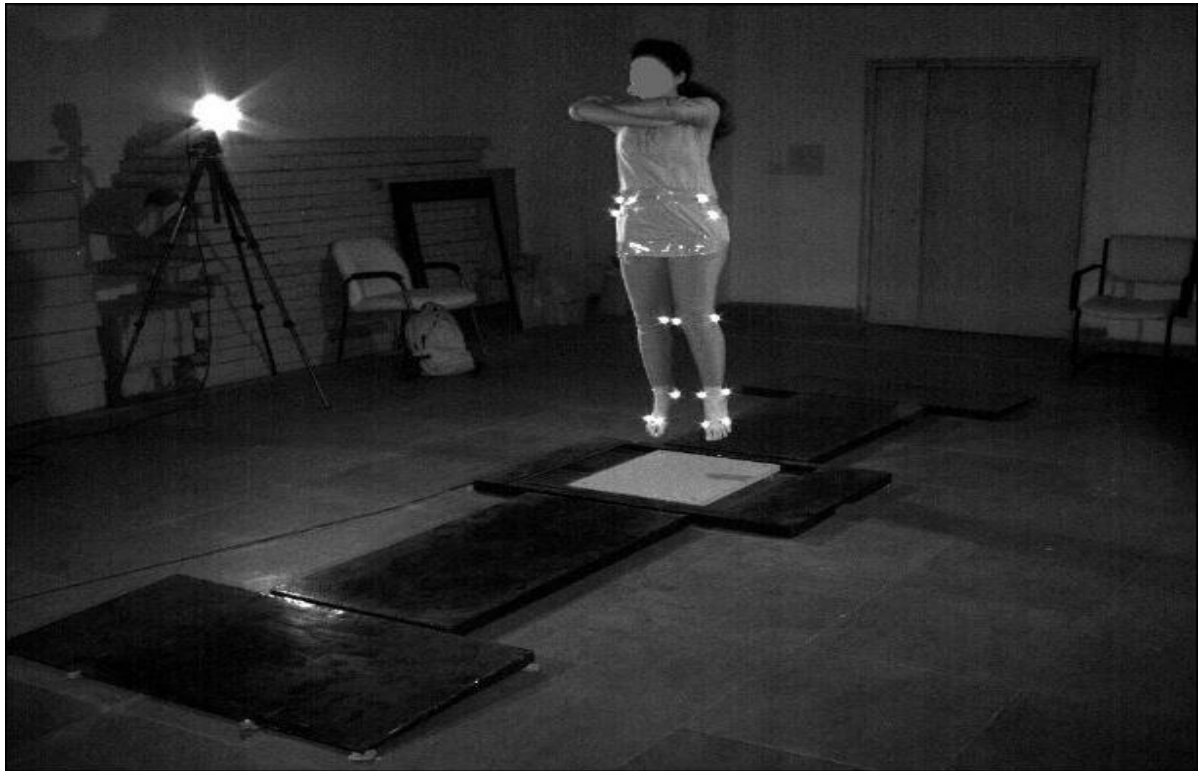


Figure 4: Volunteer performing squat jump with markers and subsequently captured on 3D motion capture system

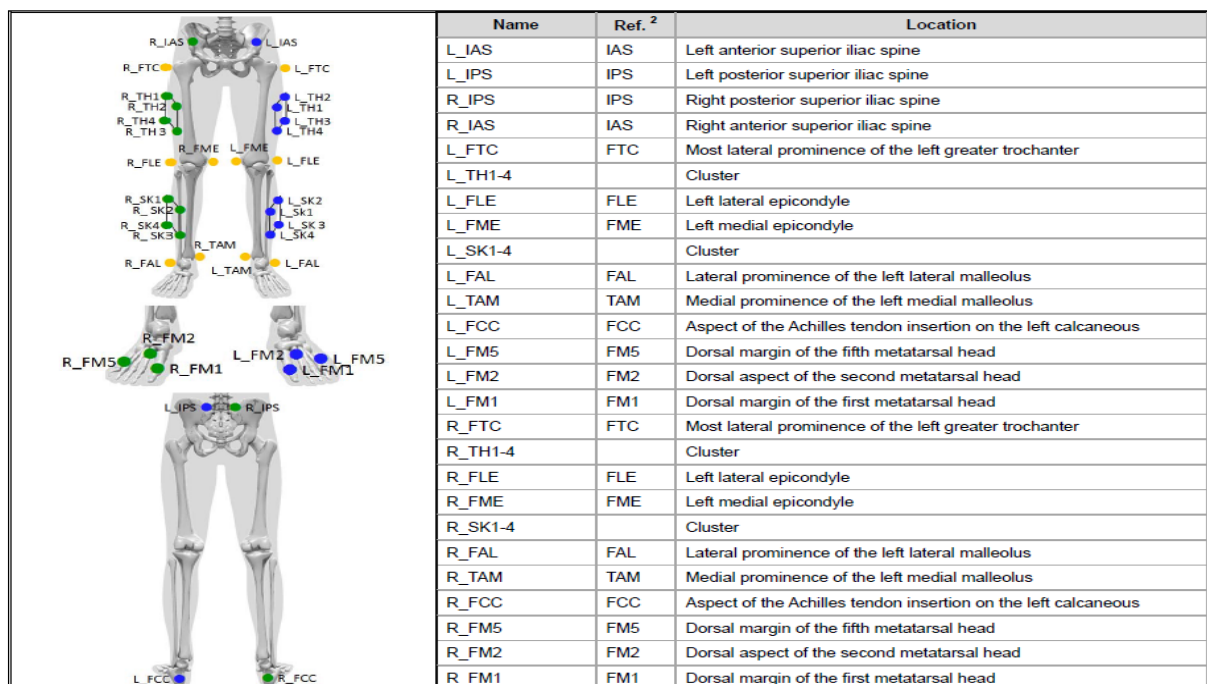


Figure 5: Markers position and naming

3.2.2 Segment Designing in Visual3D V5

3.2.2.1 Pelvis Segment

R_ICT and L_ICT are the proximal lateral and medial marker representation for the pelvis R_FTC and L_FTC are the distal lateral and medial marker representation for pelvis respectively.

3.2.2.2 Thigh Segment

Visual3D treats the thigh as a geometrical primitive. The proximal radius is the geometrical radius of the proximal end of the thigh. Calipers can be used to measure or the radius can be defined as one quarter of the distance between the greater trochanters. For proximal part FTC is selected as the proximal lateral part of the thigh and none is selected for the proximal medial part of the thigh. For distal part FLE is selected as the lateral position and FME is selected as medial position.

3.2.2.3 Shank Segment

Consistent with our recommendation for the thigh, we recommend that users avoid the lateral knee marker as a tracking marker unless the medial knee marker is also a tracking marker. FLE and FME are selected as proximal lateral and medial part of the shank. FAL and TAM are selected as the distal lateral and medial part of the shank.

3.2.2.4 One Segment Foot

This model is consistent with a one segment foot segment. FAL and TAM are selected as proximal lateral and medial part of the shank. FM5 and FM1 are selected as the distal lateral and medial part of the shank. Whenever required the orientation of the segment is modified by using 'scaling', 'rotation' and 'move' options.

3.3 Procedure

Two modes of trials were recorded for each participant, one for squat jump and another for counter-movement jump. Each trial presented one cycle of the jump. For each participant at least three sets of trials were conducted. From this set a single trial containing a clean jump was selected. A clean trial is defined as one in which all marker trajectories are detected throughout the jump cycle and hence no segmental deformation will occur during post processing the 3D model. The markers of the captured data are named and exported in the .c3d file format for analysis of the captured data. The .c3d files were imported into Visual3D software to analyze different kinematic and kinetic parameter related to the jump. The model of the lower body is designed using the Visual3D software (**Figure 6(a), (b)**).

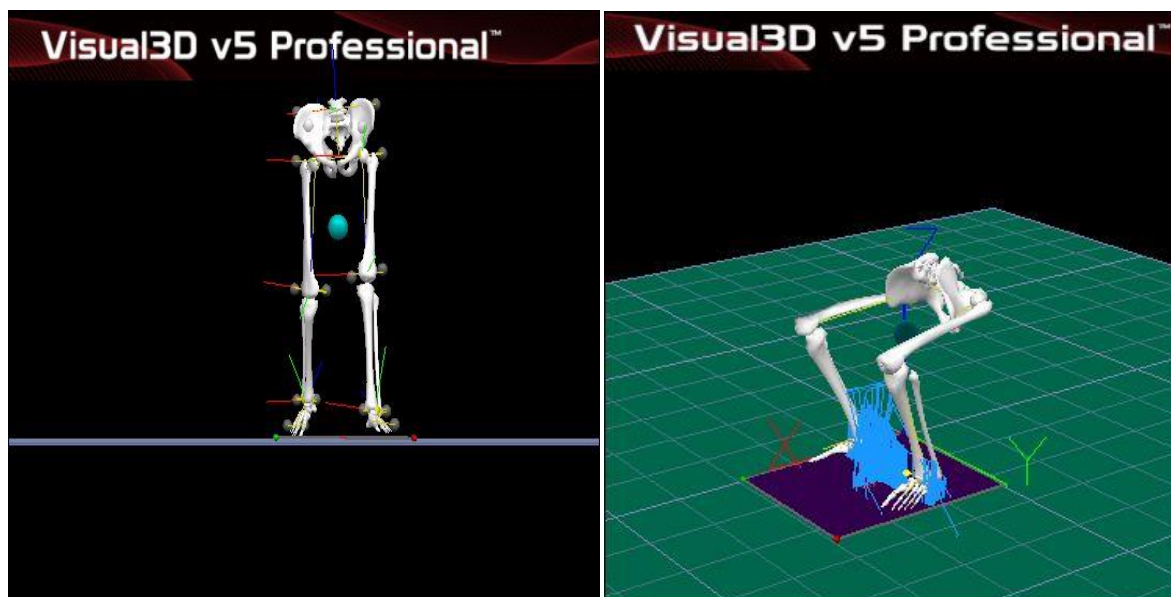


Figure 6: Model developed by visual3D V5 professional (a): the lower body model, (b): crouch position

Various plots of kinematic and kinetic data were custom defined and the generated reports were then processed by a low pass filter. Data interpolation was carried out so as to obtain a smooth and continuous graph. The useful region from the graphical plots were

extracted and used for analyzing the jump. The jump height was measured as a difference of the maximum height achieved by the center of mass (COM) during flight phase and the height of the COM while standing still. The ankle angle was defined as the angle between the foot and shank segments of the skeletal model. The knee angle was defined by the angle between the shank and the thigh segments of the skeletal model. Similarly the hip angle was defined as the angle between the pelvis and thigh segments of the skeletal model. All temporal plots of the kinematic data, i.e. joint angles were calculated on the Y-Z plane. Temporal plots of GRF, ankle angle, knee angle, and hip angle were generated in Visual3D V5 professional software. The result and analysis of this study are presented in the next chapter.

Chapter 4

Results and discussion

4.1 Kinetic analysis

4.1.1 Analysis of GRF during the Squat jump and counter-movement jump

The pattern of the ground reaction force of the jump is studied in four phases. The first is crouch phase, push-off phase, flight phase, and landing phase. The plots shown in **Figure 8 (a) & (b)** below represent the GRF acting normal to the ground for the squat jump and CM jump respectively. Even though the jump height varies in case of athletes and non-athletes, still the pattern of GRF remains distinct for squat jumps and CM jumps.

The weight of the volunteer, whose jump pattern is to be analyzed, is 553.65 N. When the participant is in the crouch phase the GRF in normal direction decreases as the COM of the body and deviates from the normal direction to the negative X-direction. The force applied is distributed among the X-, Y-, and Z-direction. In the crouch phase, (shown in **Figure 7**) the GRF decreases first and then the body accelerates upwards in the push-off phase to achieve the required force to take-off from the ground. The body accelerates with a linearly increasing acceleration in the push-off phase. When the body gets enough force to take-off the body goes in the flight phase where the GRF values is found to be 0N at the flight phase for both squat and CM jumps. The time of flight in case of counter-movement jump (0.48s) is more than that of squat jump (0.44s).

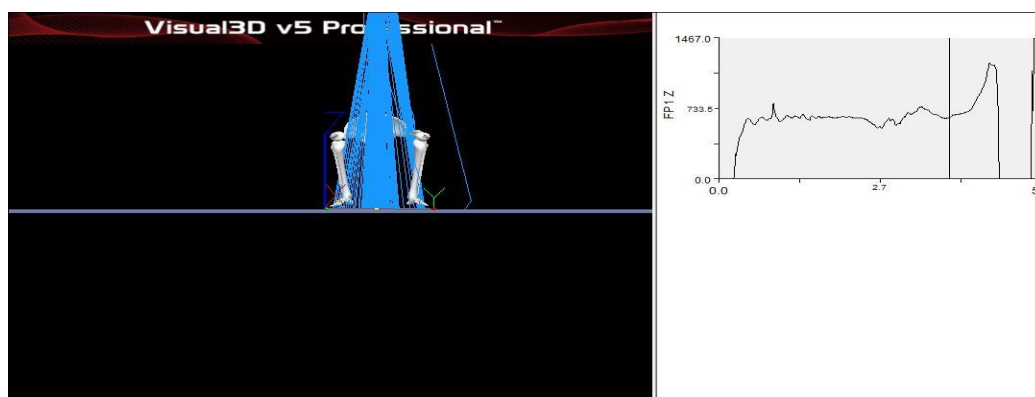


Figure 7: 3D model showing crouch phase of squat jump and the GRF plot

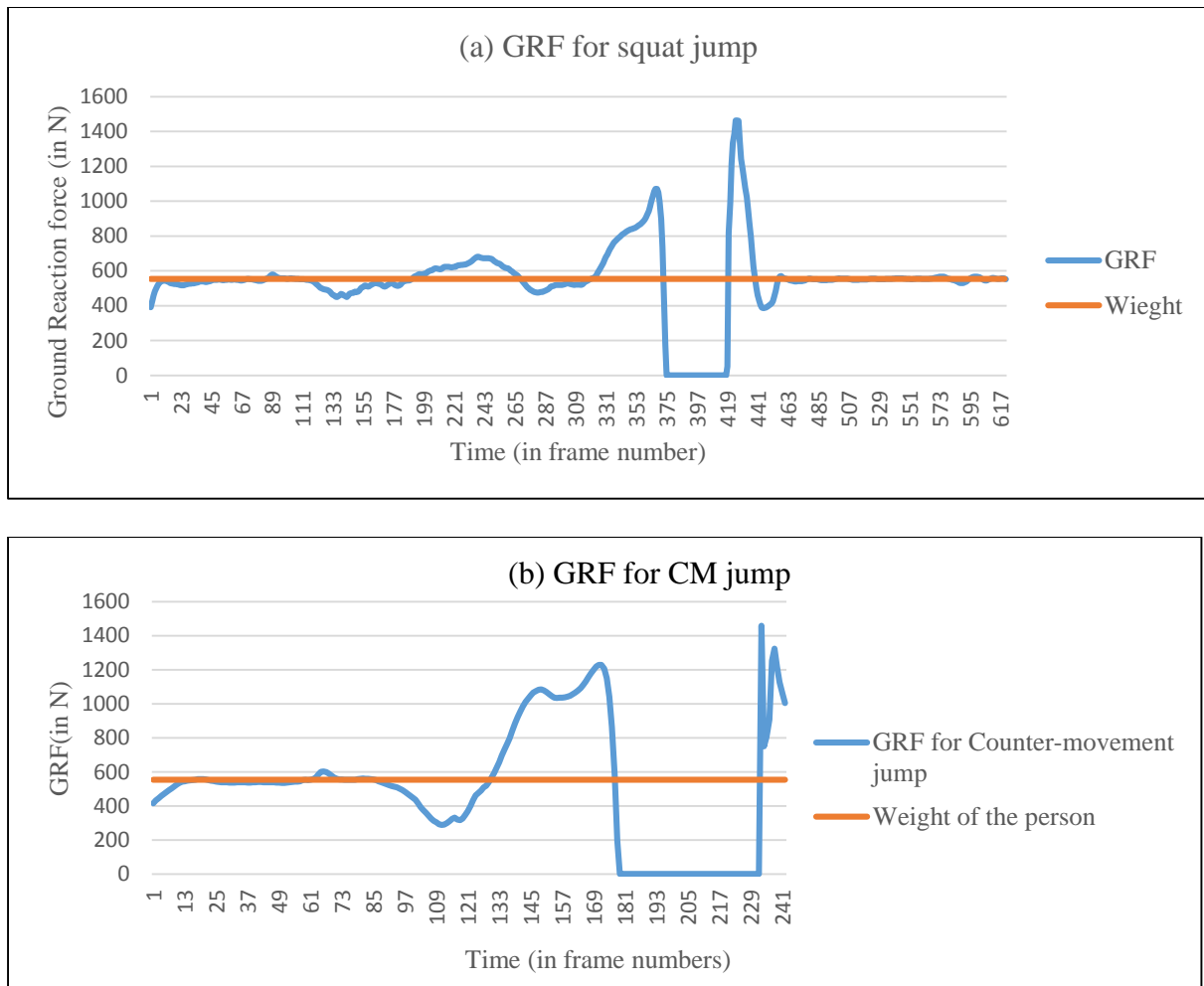


Figure 8: GRF pattern curve for (a) squat jump, (b) Counter-movement jump

4.1.2 Acceleration plots for an athlete and a non-athlete

Acceleration plots provide a distinct advantage in comparing the jump patterns of different individuals in that the ‘mass’ term is removed from the equation. An athlete and a non-athlete with nearly same body mass ($60 \pm 1 \text{ Kg}$) and comparable height (1.78 ± 0.05) were chosen from the list of volunteers. The athlete achieved a jump height of 0.414m and 0.489m whereas the non-athlete achieved a jump height of 0.31m and 0.44m in squat jump and CM jump respectively. A comparative set of study of the acceleration plots is provided in **Figure 9 and 10**. For the squat jumps GRF and acceleration pattern (**Figure 9 (a) & (b)**) obtained was found to be nearly identical for both athletes and non-athletes. The only difference was the time of flight that was found to be 0.56s for athlete and 0.46s for non-athlete in this particular

case which indicates towards a greater jump height for the athlete. Similarly for CM jump the athlete had a greater time of flight as compared to non-athlete ((Figure 10 (a) & (b)).

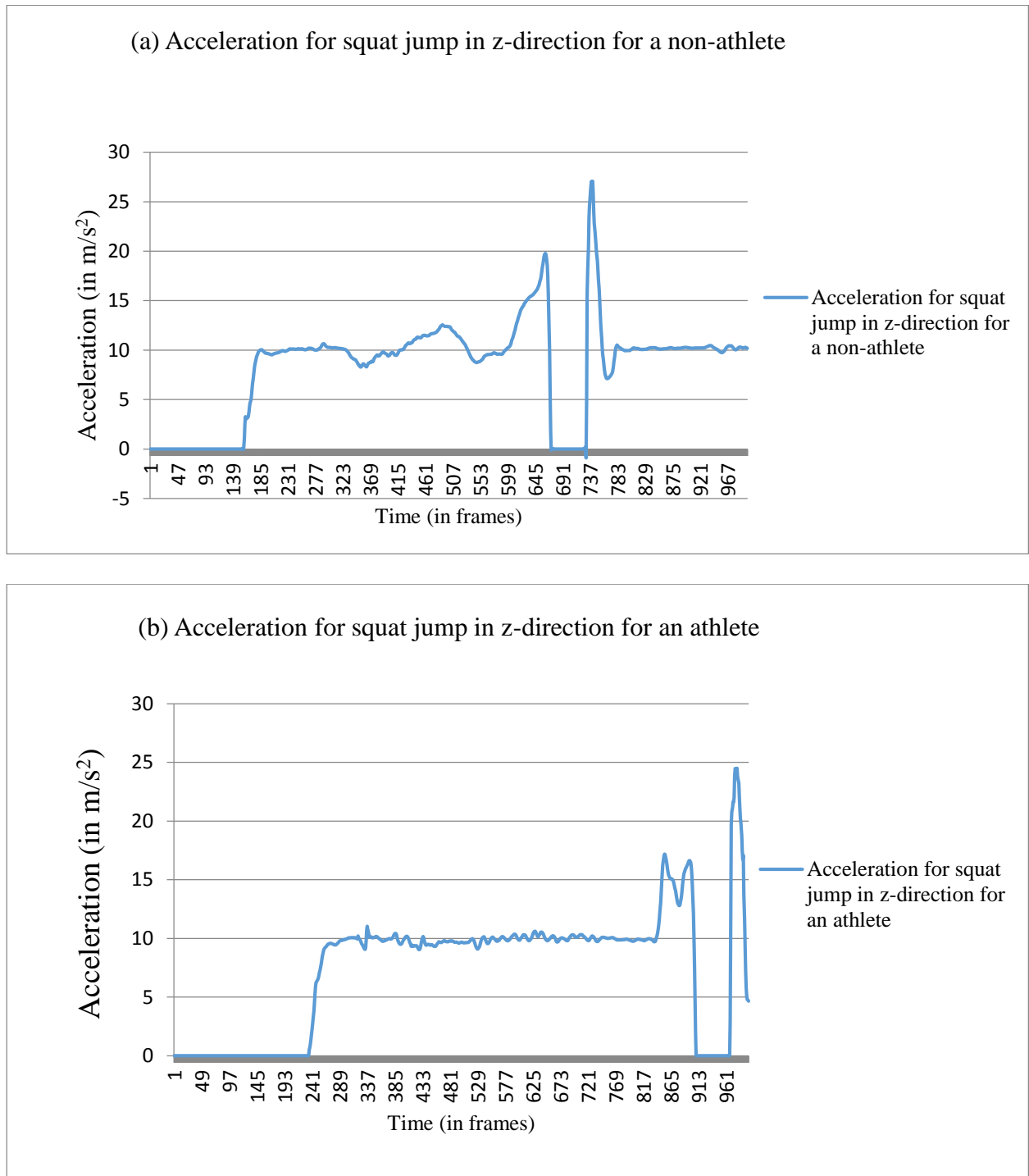


Figure 9: Acceleration of squat jump for (a) a non-athlete, (b) an athlete

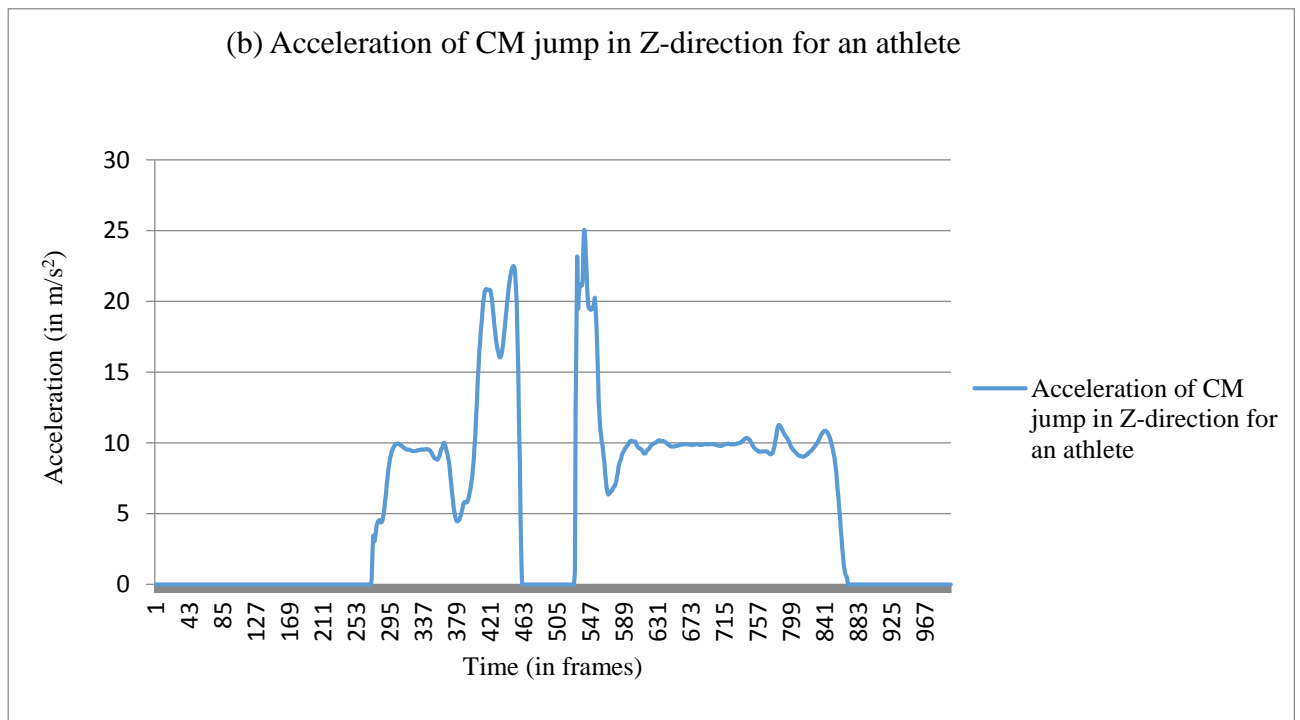
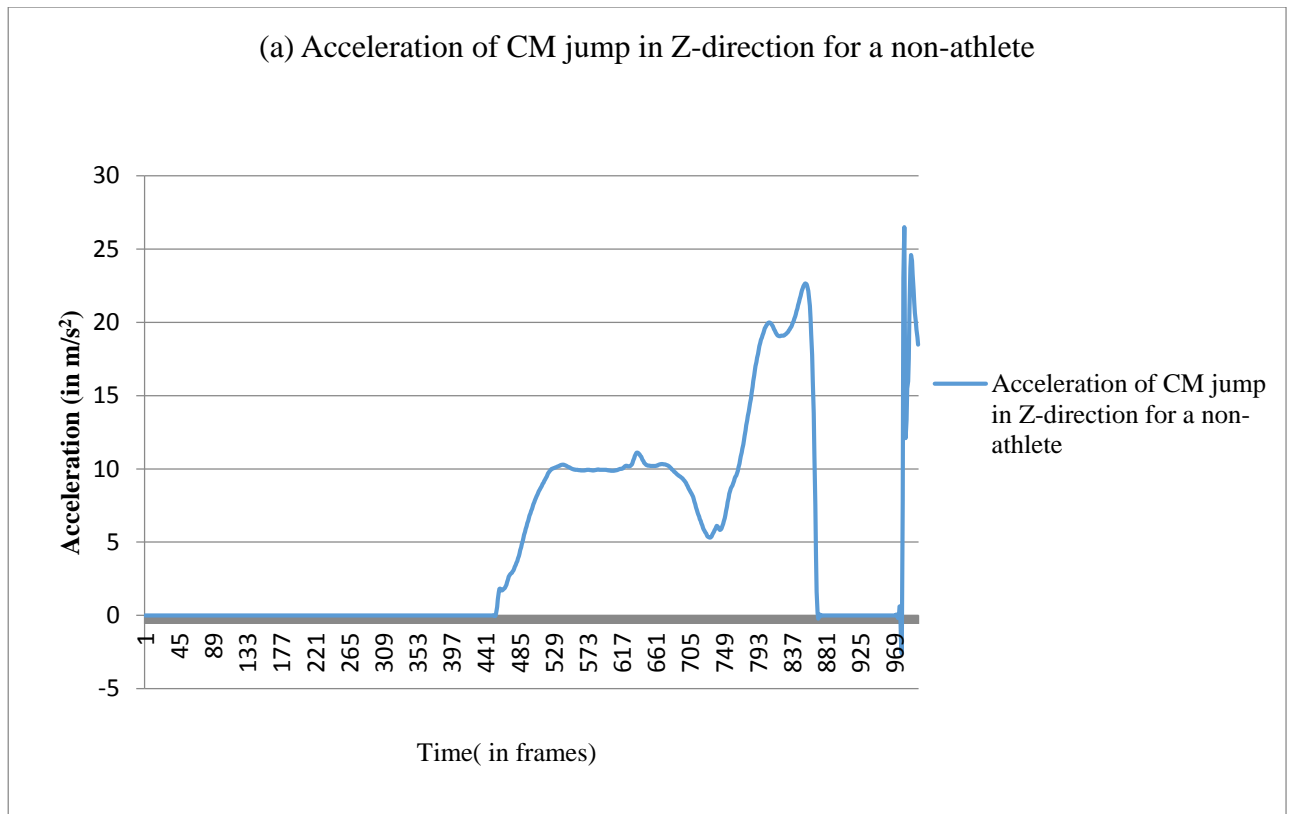


Figure 10: Acceleration of CM jump for (a) a non-athlete, (b) an athlete

4.1.3 GRF analysis before take-off for squat jump and counter-movement jump

The graph (**Figure 11**) below represents the plot of GRF values before take-off of the jump. It can be clearly observed that the GRF for the counter-movement jump is greater than that of squat jump.

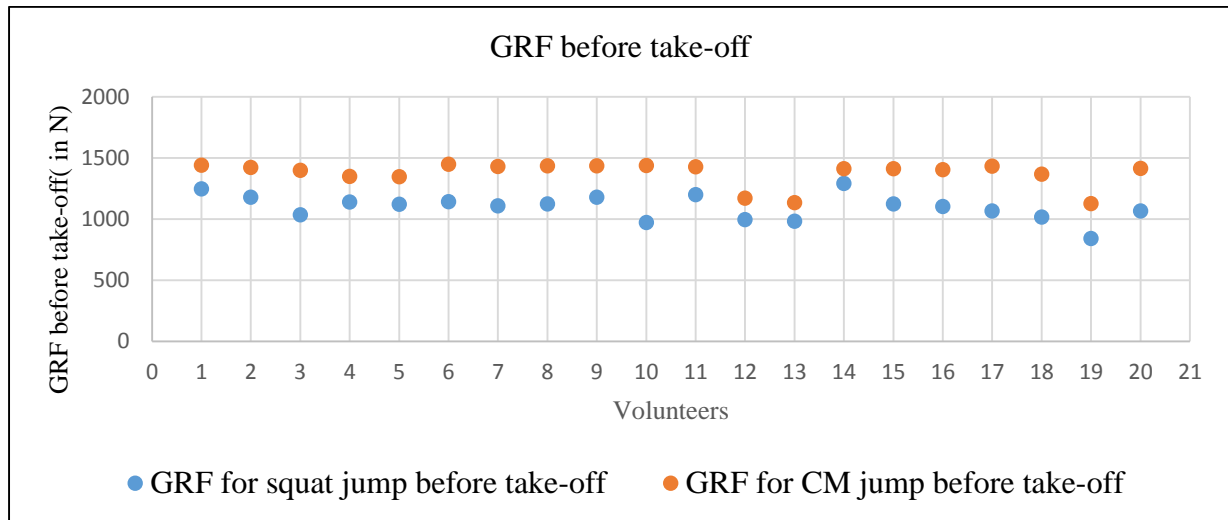


Figure 11: GRF before take-off plot for squat and counter-movement jump for all volunteers

4.2 Analysis of jump height for squat jump and counter-movement jump

By analyzing the jump height achieved by the volunteers it is found that the jump height for the counter-movement jump is more than the jump height achieved by the squat jump for both athletic and non-athletic volunteers (**Figure 12(a), (b)**). There is plot of the height difference between the squat jump height and counter-movement jump height. On an average the difference varies from 0.06m to 0.11m for the non-athletes whereas the difference varies from 0.6m to 0.14m for the athletes.

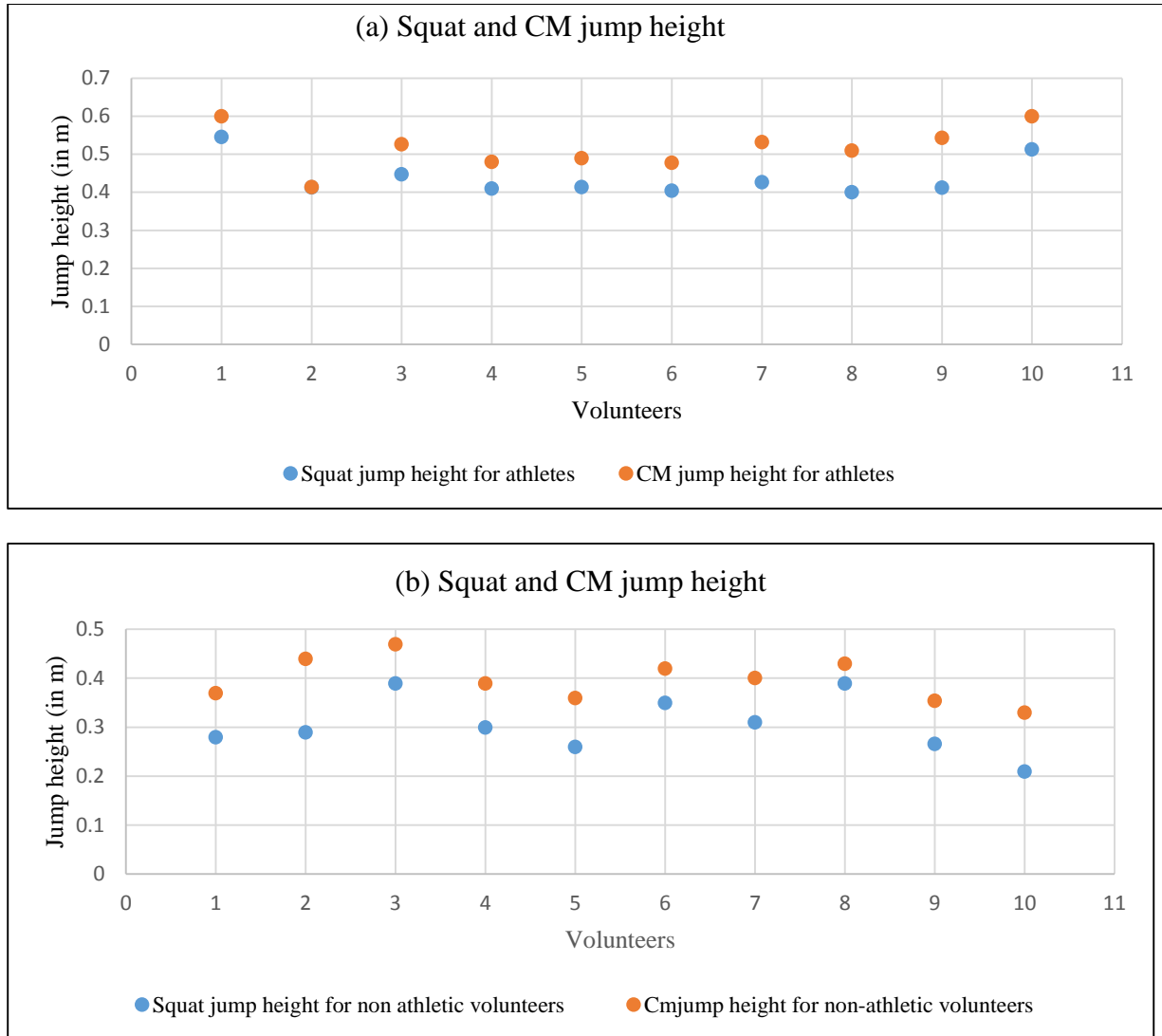


Figure 12: Scattered plot of squat and counter-movement jump height for (a) athletes, (b) non-athletes

4.3 Relation between jump height and knee angle during push-off phase of the jump

From the plot (**Figure 13(a)**) given below it can be seen that the knee angle of the athletes in case of CM jump varies from 80^0 to 100^0 . For squat jump the knee angle varies within the range of 80^0 to 140^0 . The knee angle between 80^0 and 100^0 shows a higher concentration of large jump height in cases both squat and counter-movement jump.

From the following plot (**Figure 13(b)**) knee angle for squat jump of non-athletes was observed to be in the range of 100° to 140° . For CM jump the knee angle varies mostly from 80° to 100° .

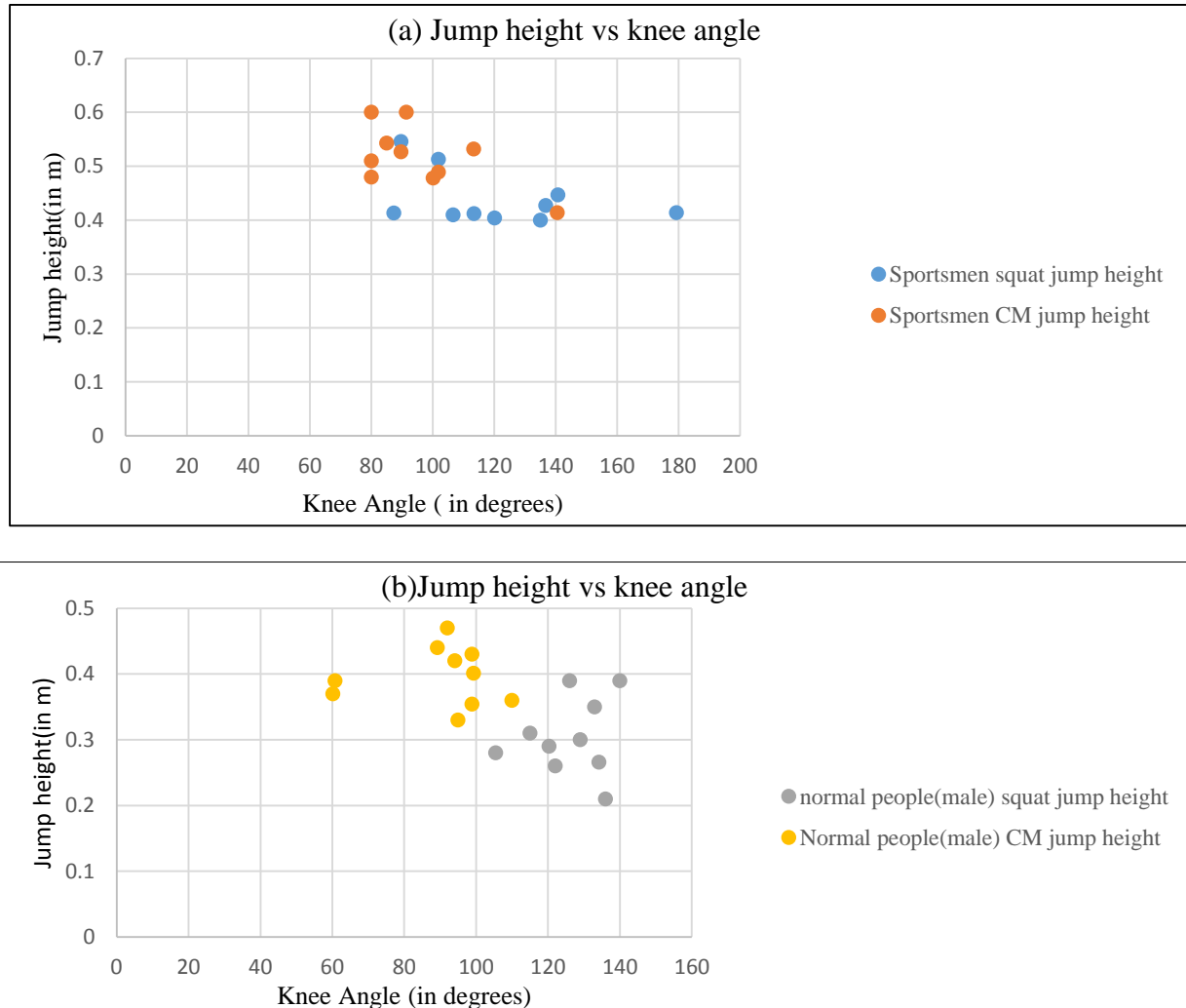


Figure 13: Scattered plot between squat and counter-movement jump height and knee angle (a) for athletes, (b) for non-athletes

From the plot (**Figure 14(a)**) below it is clearly observed that the athletes achieved maximum jump height as the knee angle varied between 80° and 100° . But for the non-athletes knee angle during push-off was found to be more than 100° . As of now no specific relationship has been established for the jump height with the knee angle for variation in the range of 100° to 140° .

Non-athletes and the athletes achieved more jump height when the knee angle remains between 80^0 and 100^0 . It was observed that for the knee angle below 80^0 or above 100^0 the jump height decreases drastically (**Figure 14(b)**).

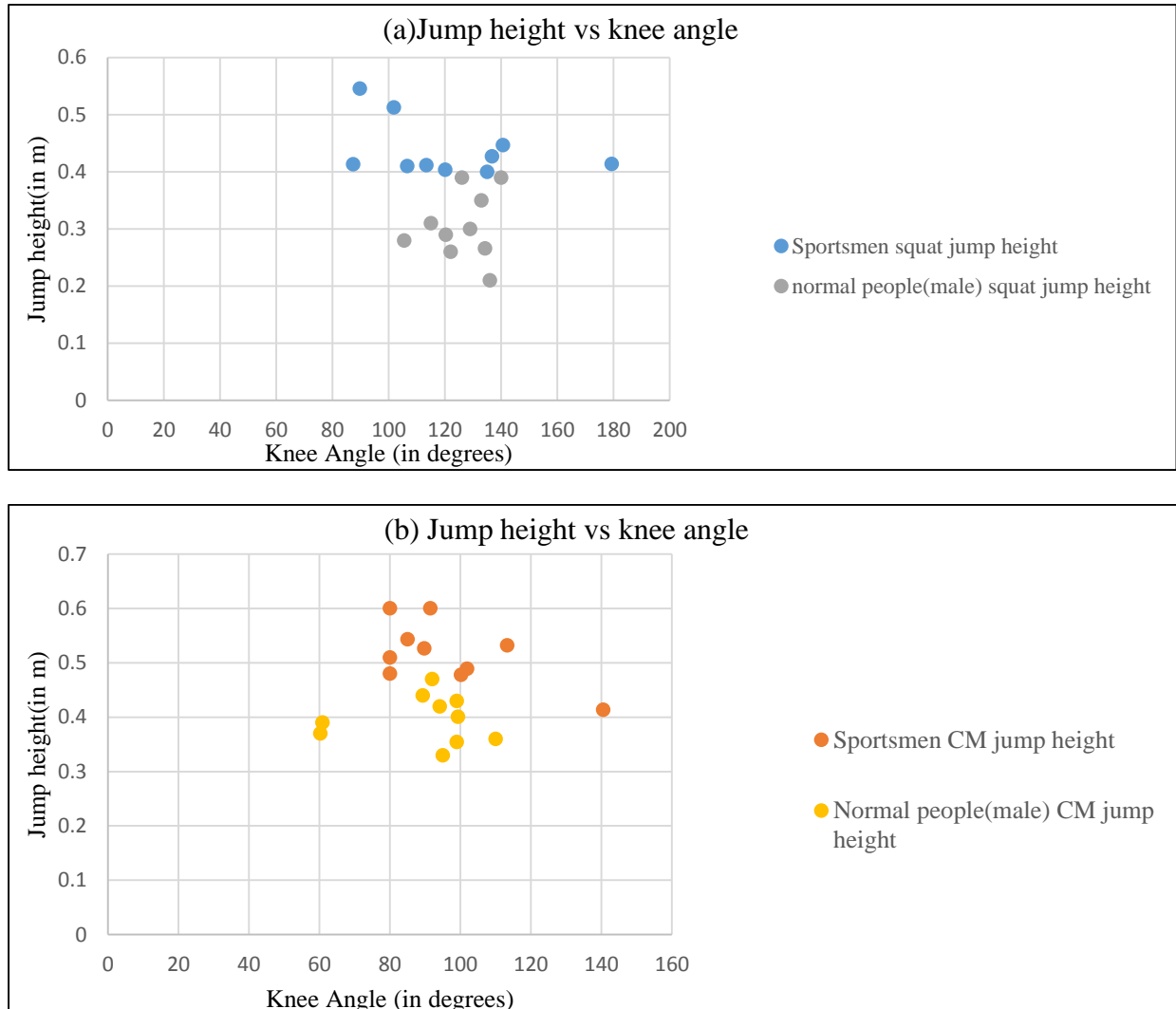


Figure 14: Scattered plot between athletes' and non-athletes' height and knee angle for (a) squat jump (b) CM jump

4.4 Relation between jump height and hip angle during push-off

From the plot (**Figure 15(a)**) below it can be observed that the for CM jump the hip angle is less than that for squat jump. It can be seen that when hip angle increases beyond 90^0 the jump height decreases. The plot below shows that at an angle of 90^0 maximum height of jump is obtained. From the plot (**Figure 15(b)**) below the jump height for counter-movement

jump the hip angle is less as compared to the squat jump. Here less hip angle represents more flexion at hip.

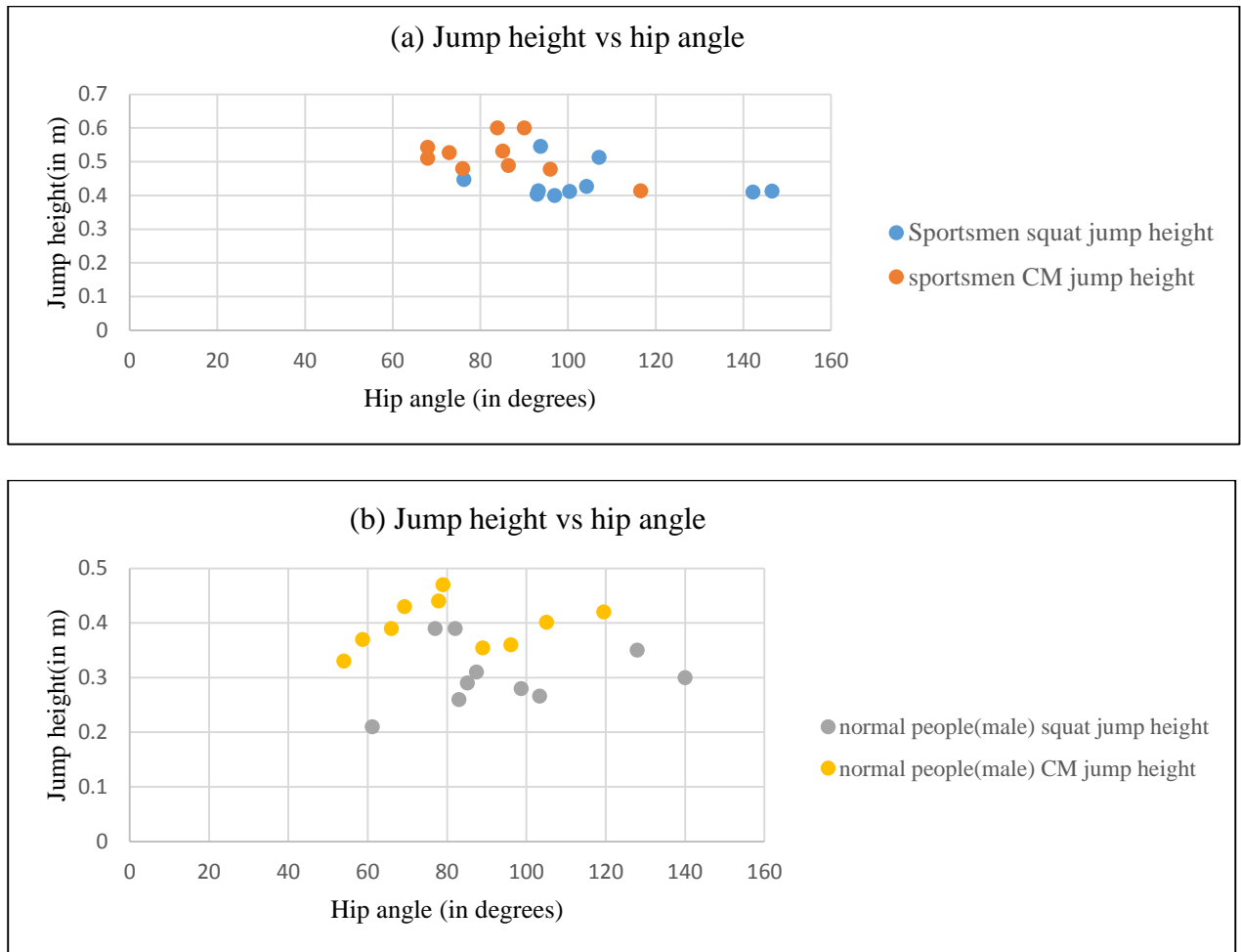


Figure 15: Scattered plot between squat and counter-movement jump height and hip angle (a) for athletes, (b) for non-athletes

4.4.3 Relation between counter-movement jump height and hip angle athletes and non-athletes

From the plot (**Figure 16(a)**) below it can be analyzed that the athletes have hip angle between 70^0 and 90^0 whereas the non-athletes have the hip angle in a long domain of hip angle. When the hip angle of the non-athletes falls in the region 70^0 and 90^0 the jump height is relatively greater than when the hip angle falls beyond the region of 70^0 and 90^0 .

The plot (**Figure 16(b)**) below represents the squat jump height for both non-athletes and athletes. The hip angle of the around 90^0 producing more jump height. But the differences between the athletes and the non-athletes are not clearly distinguished.

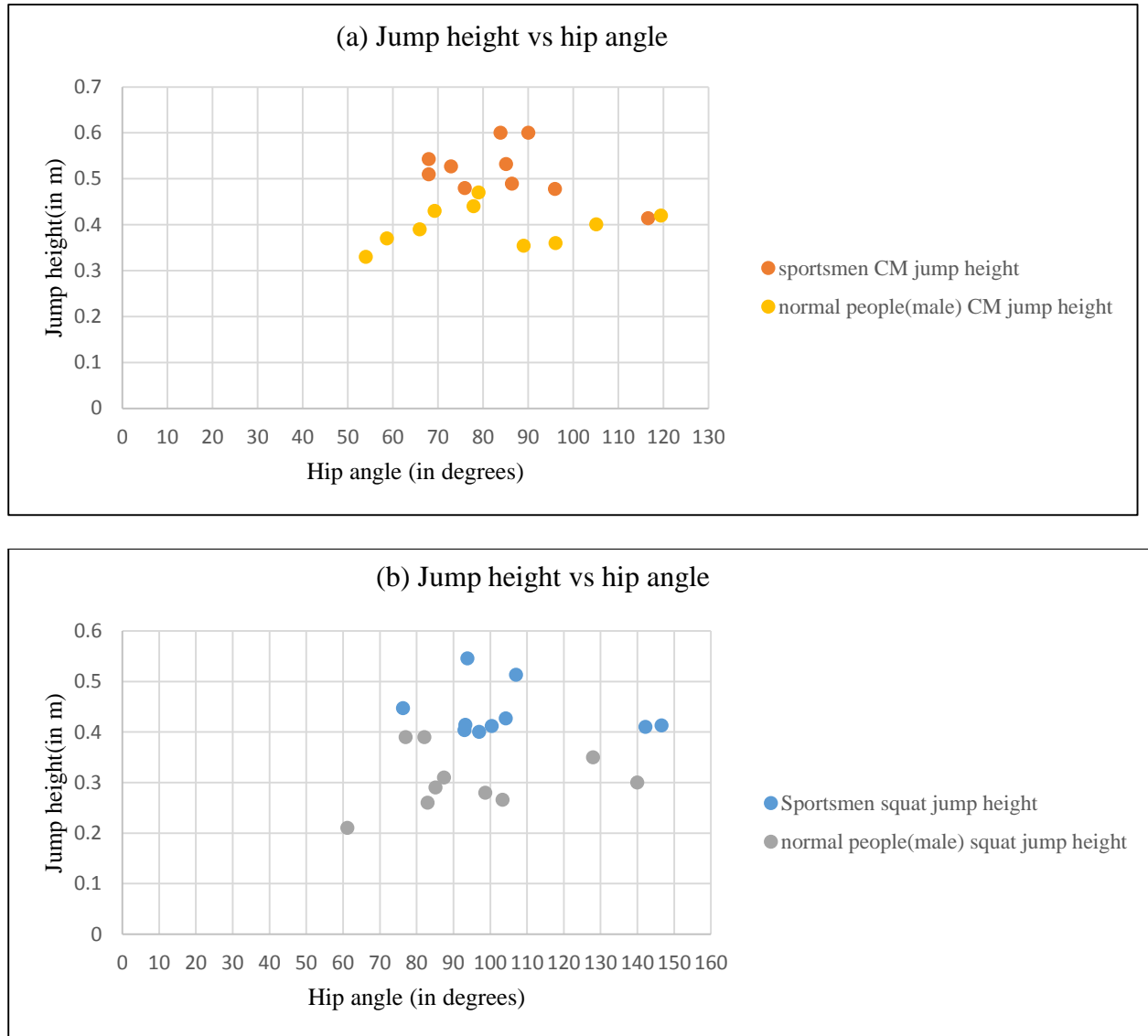


Figure 16: Scattered plot between athletes' and non-athletes' jump height and hip angle for (a) counter-movement (b) squat jump

4.5 Relation between jump height and ankle angle during push-off phase of the jump

The ankle angle of during the push-off of the athletes normally falls between 90^0 and 130^0 for squat jump. For the counter-movement jump the ankle angle range is between 100^0

and 120° (**Figure 17(a)**). The plot (**Figure 17(b)**) here represents the ankle angle varies between 95° and 110° . The squat jump and the counter-movement jump both are likely to achieve the same ankle angle during the push-off phase of the jump.

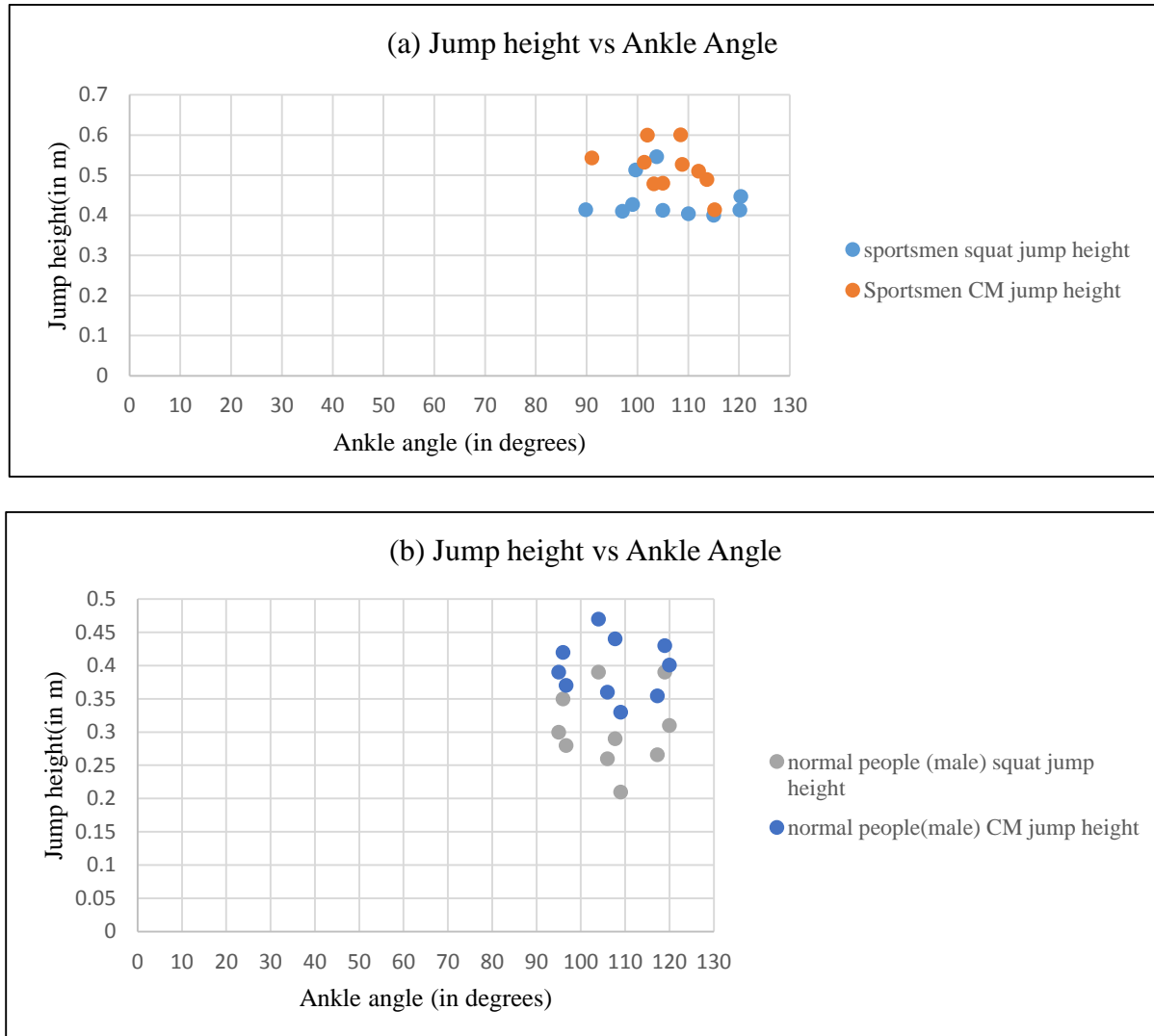


Figure 17: Scattered plot between squat and counter-movement jump height and ankle angle for (a) athletes, (b) non-athletes

The plot (**Figure 18(a)**) below shows that the maximum jump is attained is associated with the ankle angle of 90° to 120° . From the plot (**Figure 18(b)**) below the ankle angle for maximum jump height remains between 90° and 120° .

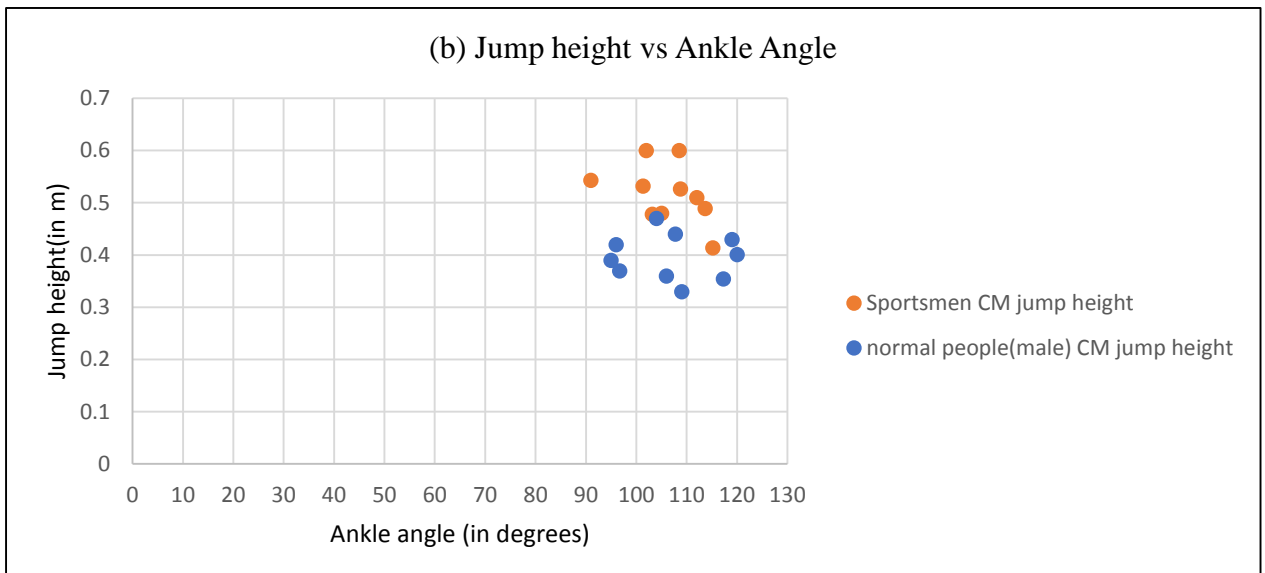
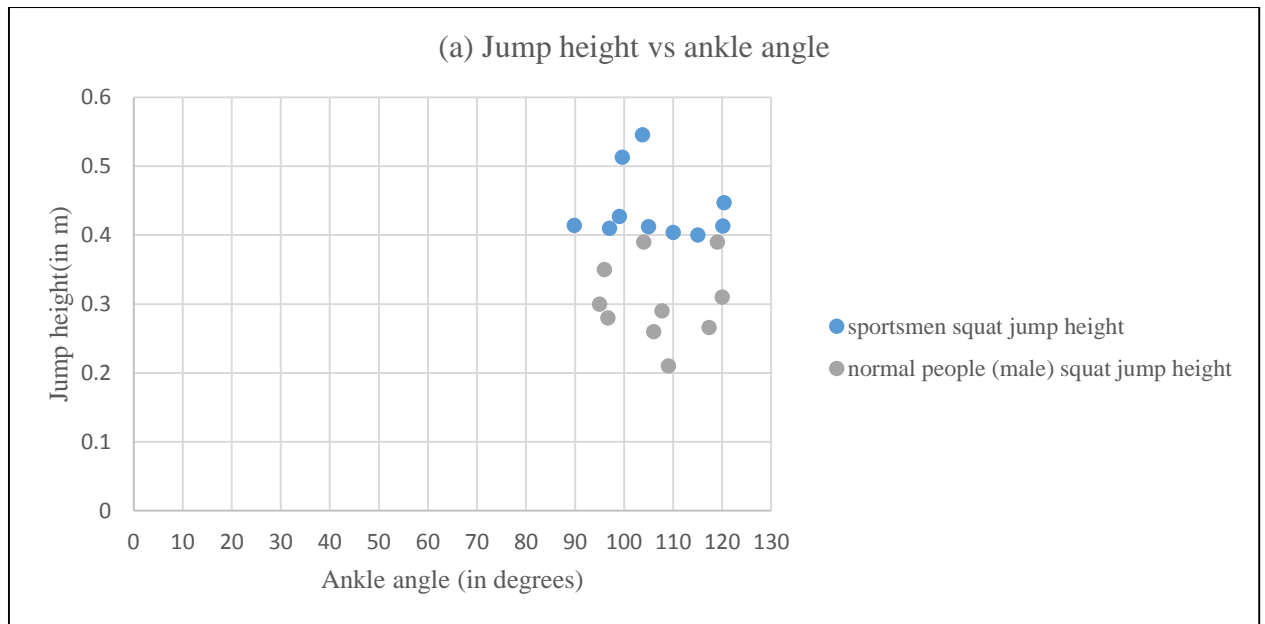


Figure 18: Scattered plot between athletes' and non-athletes' height and ankle angle

for (a) squat jump, (b) counter-movement jump

4.6 Discussion

In case of counter-movement jump the GRF value varies same way as the squat jump but the magnitude of the force at crouch phase for counter-movement jump is less than that of the squat jump and the magnitude of the force at the time take-off for counter-movement

jump (**Figure 8, 9**) is more than that of the squat jump. In case of counter-movement jump a negative impulse is created at the crouch phase.

From the impulse-momentum theory of mechanics

$$\Delta p = \int f dt \quad - eq(2)$$

Where Δp represents the change in momentum, f is the GRF, dt change in time.

As the GRF is decreasing in case counter-movement jump (figure), there will be a negative impulse and hence negative kinetic energy. Let during the crouch phase the kinetic energy be $-K_C$, potential energy be P_C , during the push-off phase the kinetic energy be K_P work done is positive during push-off phase, potential energy be P_P . According to the conservation of energy the kinetic energy at highest jump height will be zero and the sum of the above energy will be converted to potential energy. Hence $K_P - K_C$ will play an important role to decide maximum jump height. $K_P - K_C$ should be maximized to attain maximum jump height.

The crouch phase for the non-athlete shows some negative impulse and as discussed above the negative impulse will generate a negative kinetic energy which will decrease the total kinetic energy before take-off and hence the jump height is less though the acceleration before take-off is more for the non-athlete. In case of CM jump, the time of flight is less for the non-athlete than the athlete and hence the jump height is more for the athlete.

The GRF and the acceleration is more in case of CM jump in comparison to squat jump. The acceleration provides velocity and hence the kinetic energy. Hence in case of counter-movement jump the kinetic energy more just before take-off as compared to the squat jump. According to the energy conservation theorem the whole kinetic energy and the negligible potential energy will be converted to the maximum potential energy of the body which is achieved at the height of jump as the kinetic energy at that point is zero. So this is

the key reason of maximum jump height generally achieved during the counter-movement jump in comparison to the squat jump.

Knee angle of the participant during push-off plays a very important role to achieve maximum jump height. According to the experimental values the knee angle between 80^0 and 100^0 gives maximum jump height in the respective background for counter-movement jump. In case of squat jump the angle for all the non-athletes and some athletes are found to be more than 100^0 whereas some athletes attain maximum jump height at a knee angle ranged between 80^0 to 100^0 . Hence when there is more flexion the jump height decreases. This is one of the reasons why the jump height in case of the squat jump is less than the counter-movement jump. The reason behind the take-off of the body is to create a torque around the knee joint by the muscles of the leg for which the body can create some angular motion at the knee joint and that rotational energy transform into kinetic energy when rotation is restricted by the knee joint and the body goes upward. The knee angle should be such that the moment generated is maximum. As the moment is the cross product of the force and the moment arm.

$$\boldsymbol{\tau} = \boldsymbol{r} \times \boldsymbol{F} \quad - \text{eq(3)}$$

Where $\boldsymbol{\tau}$ = moment, \boldsymbol{r} = the moment arm, and \boldsymbol{F} = force applied.

To maximize the moment the knee angle should be 90^0 according to the moment formula. From the experimental value for knee angle versus maximum jump height best performance of participants is observed to lie within the range 80^0 to 100^0 .

It was found that the jump height is related to the hip angle. The hip angle of the around 90^0 producing more jump height. This can be explained by the moment theorem of mechanics. As the moment is cross product of force and moment arm, the angle plays important role for producing the maximum moment and hence maximum height can be

achieved. As the hip angle is 90^0 , maximum moment will be achieved. Hence the flexion should be such that the hip angle attains 90^0 to achieve more jump height.

During push-off, the ankle angle of the participants are normally falls between 90^0 and 120^0 . For the sportspersons the ankle angle range is between 100^0 and 120^0 . The ankle angle shows the ability of the participants to give a push-off to the body to jump higher. As the angle increases the jump height will increase but when the ankle angle crosses 120^0 the center of mass of the body comes forward and deviate from the center line of the body, and the body balance is lost, hence jump height will decrease after the 120^0 of ankle angle.

Conclusion

The study on the squat jump and the counter-movement jump was carried out using 3D Motion capture system. The study suggested that the jump height for the counter-movement jump is more than that for the squat jump. The GRF in normal direction for both the jumps represents the four different phases of the squat jump and counter-movement jump. The phases are termed as the crouch phase, push-off phase, flight phase, landing phase respectively. The GRF value decreases at the time of crouch phase and again increases with change in acceleration for counter-movement jump. The decrease in GRF value produces a negative impulse and accordingly negative kinetic energy. In push-off phase a positive kinetic energy is developed which should be more than the kinetic energy developed in crouch phase to attain maximum height. The acceleration of the GRF increases more rapidly in case of counter-movement jump. The jump height varies with respect to knee angle and hip angle. From the analysis it is found that the athletes achieve maximum jump height at a knee angle between 80° and 100° in counter-movement jump whereas for people from non-sports background the knee angle exceeds 100° which reduces the moment arm and moment will be less at the knee joint for which the jump height is less. From the above observations and analysis it is found that the jump height is related to the hip angle and maximum height of jump is achieved at around 90° - 100° of hip angle. This can be explain by the moment theorem of mechanics. As the resultant moment is a cross product of force and moment arm, the angle plays important role for producing the maximum moment and hence maximum height can be achieved. As the hip angle is 90° , maximum moment will be achieved. Hence the flexion should be such that the hip angle and knee angle attain 90° to achieve maximum jump height. The ankle angle of before the take-off of the participants normally falls between 90° and 120° . As of data collected till now no specific relationship of jump height with ankle angle is established. But irrefutably, the stability of the jump depends on the ankle angle.

Scope for Future Work

Present work shows the analysis of the lower body for squat jump and counter-movement jump. Further, full body analysis should be carried out for better understanding of different jumps. Moreover the analysis should be carried out on sports persons from different background and a regression analysis can be performed. The analysis carried out in this study is based on the different joint angle (ankle angle, knee angle, hip angle) and their relationship with jump height. The jump height also depends on other parameters like moments at the lower body joints, muscular activity and muscle strain. Future work may be focused on studying these musculoskeletal properties. Hence these points are important to have a sound idea on squat jump and counter-movement jump and to suggest any important implications which these findings may have for athletes. If a particular range of knee and hip angle is found to favor maximum jump height a device may be designed to train athletes during workouts to carry out jumps within the same angles in order to achieve maximum performance.

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